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RESEARCH ARTICLE

Mapping Climatological Trends in Soil Moisture Variability Across Nigeria

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Abstract

This study examines long-term trends and variability in soil moisture across Nigeria using gridded Tropical Applications of Meteorology using Satellite (TAMSAT) data spanning 1983–2023. Monthly and annual mean soil moisture were analysed across four depth layers to assess spatial and temporal patterns. Results reveal a strong north–south gradient, with mean surface soil moisture in the southern coastal zones (~30–35 kg m⁻²) far exceeding values in the northern Sahel (0–5 kg m⁻²). Soil moisture magnitude and seasonal persistence increase substantially with depth, with the deepest layer (100–300 cm) storing nearly an order of magnitude more water than the surface. In southern Nigeria, deep-layer values reach approximately 700–800 kg m⁻², compared to about 150–200 kg m⁻² in the far north. Trend analysis highlights a marked latitudinal contrast: arid northern regions exhibit significant wetting, with Sen's slope in the deepest layer approaching +0.10 kg m⁻² yr⁻¹, while the humid south shows weak or slightly negative trends (~–0.021 kg m⁻² yr⁻¹). Temporal decomposition indicates that these trends are most persistent in subsurface layers, with the deep soil reservoir gaining 47.6 kg m⁻² over the 41-year period. Post-drought wetting in northern Nigeria contrasts with prevailing African drying narratives. Its strong manifestation in deep soil layers highlights the critical role of subsurface moisture in assessing long-term hydroclimatic change and supports improved, region-specific water resource management and climate adaptation strategies nationwide.

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1. INTRODUCTION

Soil moisture within the unsaturated zone is a critical component of Earth's climate system, exerting strong control on hydrological processes, surface energy balance, and chemical transport at the land surface (Liao *et al*., 2017; Cai *et al*., 2023). Although it represents only a small fraction of total terrestrial water, soil moisture acts as a primary buffer of precipitation inputs, sustaining evapotranspiration and streamflow between rainfall events (Liao *et al*., 2017; Zhu *et al*., 2023). Through its influence on surface energy partitioning, soil moisture governs land–atmosphere coupling: dry soils suppress evapotranspiration and enhance sensible heat flux, warming the near-surface atmosphere, whereas wet soils promote latent cooling and cloud formation (Williams & Torn, 2015; Zhu *et al*., 2023). Because soil moisture integrates atmospheric forcing with subsurface processes, it plays a key role in regulating climate extremes, ecosystem dynamics, and hydrological feedbacks (Seneviratne *et al*., 2010; Zawadzki & Kędzior, 2014; William, 2024; Sun *et al*., 2025).

Given its central role in land–atmosphere interactions, global and regional assessments of soil moisture have expanded considerably in recent decades. A growing body of evidence indicates persistent drying trends across many land areas under recent warming. Empirical analyses reveal widespread increases in aridity since the mid-20th century, though with pronounced spatial heterogeneity (Sheffield & Wood, 2008; Dai *et al*., 2018). Reanalysis products and satellite observations corroborate these patterns, documenting persistent soil moisture declines in the extratropics since the 1970s (Liu & Yang, 2022), with slight drying trends in multiple reanalyses and significant multidepth declines across the Mongolian Plateau (Liu & Yang, 2022). These findings generally support the tendency for drier areas to become drier under global warming, although distinct regional variations are observed (Trenberth *et al*., 2014; Zaitchik *et al*., 2023). Consistent with this, wet regions tend to experience enhanced wet-season moisture, while dry regions undergo intensified dry-season deficits, amplifying seasonal contrasts (IPCC, 2021). Large-scale analyses further indicate that nearly half of the global vegetated area exhibits declining surface soil moisture, with approximately 8–9% of land showing significant drying and a comparable fraction exhibiting wetting (Lal *et al*., 2023; Mohseni *et al*., 2023). Such drying has far-reaching consequences for biodiversity, carbon cycling, and food security, particularly in vulnerable regions (Lal *et al*., 2023; Mohseni *et al*., 2023).

West Africa lies at a sensitive transition between humid tropical climates and the arid Sahara, where soil moisture both reflects and regulates regional climate dynamics. It is the dominant component of terrestrial water storage and a key mediator of West African monsoon–ecosystem interactions, enhancing moisture recycling and convective rainfall (Koster *et al*., 2004). Despite its importance, long-term soil moisture trends in the region remain poorly characterised due to sparse in-situ observations, with existing knowledge relying largely on satellite missions and reanalyses (Nicholson, 2013). Nigeria exemplifies these contrasts through a pronounced north–south climate gradient, ranging from humid southern monsoon regimes to semi-arid Sahelian conditions, with strong implications for rainfed agriculture, which accounts for 70–90% of national food production (Adejuwon, 2006; Ologeh *et al*., 2018). Historical droughts and floods have repeatedly exposed the vulnerability of crops and food security to soil moisture variability (Tarhule & Woo, 1998; Ologeh *et al*., 2018). Consequently, changes in Nigeria's soil moisture regime are likely to drive cascading impacts across agriculture, water resources, ecosystem stability, and climate regulation (Adejuwon, 2006; Ologeh *et al*., 2018).

Despite its central role in land–atmosphere interactions and food security, long-term soil moisture dynamics in Nigeria remain underexplored. Most hydroclimatic studies have focused on precipitation and temperature variability (Olaniyi *et al*., 2013; Oguntunde *et al*., 2017; Ologeh *et al*., 2018), with soil moisture changes inferred indirectly from drought indices or vegetation proxies that do not explicitly represent root-zone conditions. While localized field studies and satellite missions such as SMOS and SMAP provide valuable insights into surface soil moisture, they lack the spatial continuity or temporal depth required for national-scale climatological assessment. This study addresses this gap by presenting the first comprehensive, multi-decadal (1983–2023) analysis of soil moisture variability across Nigeria using the TAMSAT soil moisture product. Unlike previous work, this study simultaneously examines spatial gradients across agroecological zones, depth-dependent soil moisture behaviour, seasonal cycles, and long-term trends using robust statistical methods. In doing so, it provides new evidence on latitudinal contrasts, subsurface moisture persistence, and potential post-drought recovery in northern Nigeria relative to weak or negative trends in the humid south, thereby advancing understanding of soil moisture dynamics in a region where direct long-term observations remain scarce.

2. MATERIAL AND METHODS

2.1 Study Area

Geographically, Nigeria lies between latitudes 4° N and 14° N and longitudes 2° E and 15° E (Iyiola *et al.*, 2020), covering a total land area of approximately 923,768 km² (Ugwu & Zewotir, 2020; Kehinde *et al.*, 2021; Okunlola *et al.*, 2021; *Landscapes and Landforms of Nigeria*, 2023). The country's topography is predominantly low-lying to gently undulating, with vast plains and occasional highlands such as the "High Plains of Hausaland" in the north, reaching elevations of about 532 m above sea level (Usman *et al.*, 2018). Nigeria's climate is primarily tropical and is governed by the seasonal movement and interaction of the moist south-westerly monsoon winds from the Atlantic Ocean and the dry north-easterly continental air masses from the Sahara Desert (Nwachukwu *et al.*, 2020). This interaction defines the country's two dominant seasons; the wet and dry seasons (Umar *et al.*, 2018), and produces a pronounced south–north gradient in rainfall and temperature (Akinwumiju *et al.*, 2020). Annual rainfall amounts and the duration of the rainy season decrease progressively from the humid southern coast to the arid northern interior (Usman *et al.*, 2018), while temperature generally increases northward (Shiru *et al.*, 2020).

Based on rainfall distribution, vegetation, and ecological characteristics, Nigeria is divided into several agroecological zones arranged along the south–north gradient: Humid forest, Derived Savanna, Sourthern Guinea, Mid Altitude, Northern Guinea, Sudan Savanna, and Sahel Savanna (Usman *et al.*, 2018) (see Figure 1). The southern coastal and rainforest zones, including the Guinea Coast between approximately 4° N and 8° N (Nwachukwu *et al.*, 2020), experience a humid monsoon climate with annual rainfall often exceeding 2,000–3,000 mm (Ayanlade *et al.*, 2020; Shiru *et al.*, 2020). Rainfall typically begins in March or April and extends until October, with a bimodal pattern marked by a brief “August break” (Nwachukwu *et al.*, 2020). Mean monthly precipitation frequently surpasses 200 mm, and temperatures range from 28 °C to 37 °C, with minima around 18 °C (Umar *et al.*, 2018; Ayanlade *et al.*, 2020).

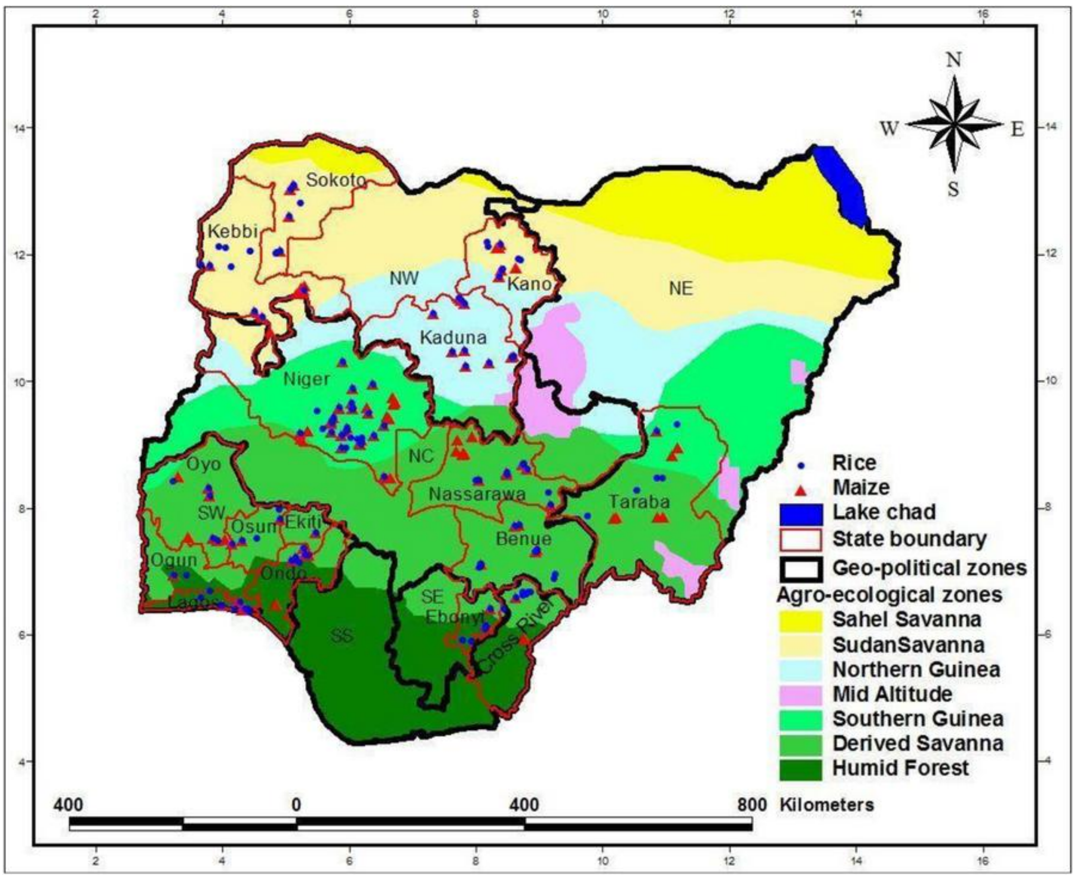

Figure 1: Geographical map of Nigeria depicting the delineation of its agroecological and geopolitical regions (Kehinde *et al.*, 2021)

Further north, the Guinea Savanna zone (roughly 8°–11° N) represents a transitional tropical savanna climate, classified as Aw under the Köppen system (Sani & Alhassan, 2019; Shiru *et al.*, 2020). It receives an average annual rainfall of about 1,000 mm and supports moderately drained Alfisols derived from the Chad Formation and Basement Complex parent materials (Sani & Alhassan, 2019). Mean monthly temperatures vary between 20 °C and 37 °C. The northernmost regions, comprising the Sudan and Sahel Savannas (approximately 11°–14° N), exhibit semi-arid to arid climatic conditions (Usman *et al.*, 2018; Shiru *et al.*, 2020). Annual rainfall in these zones is low, ranging from about 500–650 mm in the Sudan Savanna to below 400 mm in the Sahel (Usman *et al.*, 2018; Ayanlade *et al.*, 2020; Shiru *et al.*, 2020). The rainy season here is short, lasting from May or June to September (Nwachukwu *et al.*, 2020). Daytime temperatures can exceed 45 °C in the extreme north during the pre-monsoon months, while minimum temperatures can drop to about 12 °C during the wet season (Umar *et al.*, 2018; Shiru *et al.*, 2020). Rainfall variability has been particularly high across the Sudano-Sahelian belt in recent decades (Usman *et al.*, 2018). These climatic and ecological gradients strongly influence Nigeria's hydrology and soil moisture dynamics. Soil moisture follows the south–north rainfall pattern, remaining high and stable in the humid southern zones and declining sharply toward the arid north. This makes soil moisture a key factor in sustaining agriculture and water resources, particularly in the semi-arid and arid regions where rain-fed farming predominates and water availability is tightly linked to seasonal precipitation (Usman *et al.*, 2018).

2.2 Data Source

Soil moisture data were obtained from the TAMSAT Soil Moisture (TAMSAT-SM) dataset (https://research.reading.ac.uk/tamsat/soil-moisture). This is a gridded, satellite-driven product that provides estimates of soil moisture for all of Africa on a 0.25° × 0.25° latitude–longitude grid. The dataset is generated by running the UK Met Office JULES land surface model (with ~1 m rooting depth) forced by daily TAMSAT satellite rainfall and other meteorological inputs, and calibrated using NASA SMAP soil moisture observations. The volumetric soil moisture content was analysed for four depth layers: 0–10 cm (Depth 1), 10–35 cm (Depth 2), 35–100 cm (Depth 3), and 100–300 cm (Depth 4). The data cover January 1983 through December 2023 (41 years). All soil moisture variables were downloaded from the TAMSAT data portal in Network Common Data Form (netCDF) format for analysis. Soil moisture is reported in kg m^{-2} to represent the total water mass per unit area, which is convenient for multi-depth, column-integrated analyses. It relates to volumetric soil moisture ($m^3\,m^{-3}$) through layer thickness and bulk density, linking water fraction to total column storage.

2.3 Data Preprocessing

All data processing and analysis were carried out using open-source Python scripts and MATLAB software (institutional licence). The gridded soil moisture fields were first masked to Nigeria's national boundary. For each depth layer, daily values within Nigeria were averaged to produce a monthly mean for each grid cell. An annual mean was likewise computed by averaging the 12 monthly values for each year. Grid cells with missing or invalid data (e.g. over inland water or data gaps) were excluded by spatial masking during these computations. Each grid cell's mean was weighted by its land area (accounting for latitude) when averaging to form the countrywide soil moisture at each depth. The result of preprocessing is, for each depth layer, a continuous monthly (and annual) time series of Nigerian-average soil moisture covering 1983–2023 (to be used for climatology and trend analysis).

To quantify long-term changes in soil moisture, trend analysis was performed on the average time series at each depth. First, a linear regression was fit to the data versus time (years) to estimate the trend slope β. Specifically, β was computed by least squares as

$$\beta = \frac{\sum_i (t_i-\bar{t})(S_i-\bar{S})}{\sum_i (t_i-\bar{t})^2}, \quad (1)$$

where t_i is the time index (year) and S_i is the corresponding soil moisture value; $\bar{t}$ and $\bar{S}$ are the sample means. The nonparametric Sen's slope estimator was also applied to obtain a robust trend magnitude. Sen's slope, β_{Sen} , is the median of all pairwise slopes $(S_j - S_i)/(t_j - t_i)$ for $j > i$:

$$\beta_{\mathrm{Sen}} = \mathrm{median}\left\{\frac{S_j-S_i}{t_j-t_i}\right\}, \quad j > i \quad (2)$$

Together, β and β_{Sen} characterize the monotonic trend of soil moisture over the 1983–2023 period.

The climatological means and anomalies were computed to characterise seasonal and interannual variability. The long-term average for each calendar month m was calculated as

$$\bar{S}_m = \frac{1}{N}\sum_{y=1}^{N} S_{m,y}, \tag{3}$$

Where $S_{m,y}$ is the national mean soil moisture in month m of year , and N is the number of years (1983–2023).

Monthly anomalies were then defined by subtracting the climatology:

$$A_{m,y} = S_{m,y} - \bar{S}_m, \tag{4}$$

Which removes the seasonal cycle and highlights deviations in each month and year from the long-term average.

Finally, to decompose each depth's soil moisture time series into seasonal, trend and residual components, STL (Seasonal-Trend decomposition using Loess) was applied. STL is a nonparametric method that separates a time series into a smooth trend, a periodic seasonal cycle, and a remainder (residual) component. In our analysis, STL was applied to the monthly average series (for each depth) to isolate the underlying linear or nonlinear trend from the annual seasonal cycle. This decomposition facilitates visualization and interpretation of the long-term soil moisture trends relative to the characteristic seasonal cycle. Independent validation of TAMSAT-SM over Nigeria using ISMN stations has been comprehensively performed by Moses (2025). Building upon this established validation, the present work focuses on long-term variability and trend analysis rather than re-evaluation of product accuracy.

2.3 Trend significance and uncertainty assessment

Trend significance was assessed using the confidence intervals of linear regression slopes and the robustness of Sen's slope estimates. The use of Seasonal-Trend decomposition using Loess (STL) allowed explicit separation of seasonal, trend, and residual components, reducing the risk of spurious trend detection caused by seasonal aliasing. Given the strong temporal autocorrelation inherent in soil moisture time series, formal non-parametric hypothesis tests such as the Mann–Kendall test were not emphasized, as they require additional corrections (e.g., pre-whitening) to avoid inflated significance.

3. RESULTS

3.1 Spatial and Seasonal Variability of Mean Soil Moisture Across Nigeria

Figures 2–5 present the monthly mean soil moisture climatologies for Depths 1 through 4, illustrating consistently wetter conditions in the southern coastal and forest zones and much lower soil moisture in the northern Sahel across all layers. In the southern coastal and forest zones (roughly 4°–6°N), soil moisture is consistently high, with surface mean values around 30–35 kg/m² and deeper layers exhibiting even larger storage. For example, annual mean moisture in the upper 100 cm rises to ~220 kg/m², and below 1 m it reaches on the order of 700–800 kg/m², reflecting high rainfall and dense vegetation. By contrast, the arid northern Sahel (around 12°–14°N) shows very low values year-round: surface moisture is near 0–5 kg/m² and even the deepest layer only contains on the order of 150–200 kg/m² on average. These opposing extremes are evident in the colour transitions on the maps (cool blues in the north vs. warm reds in the south). East–west variations are more subtle, eastern highland areas (10°–14°E) tend to be slightly wetter than adjacent western plains, consistent with orographic enhancement of rainfall. Majorly, the Niger Delta and southeastern forest zones stand out as persistently moist regions (with soil moisture often remaining above ~70% of their annual maxima even in dry months), whereas the Lake Chad basin and northern savanna zones remain persistently dry (often <20% of southern levels). These spatial patterns are reflected in extracted grid-point values: at 4.375°N, 9.375°E, annual mean moisture is ~34 kg/m² at the surface (with ~700 kg/m² at depth), versus only ~6–7 kg/m² at 13.625°N, ~8°E (with ~195 kg/m² at depth).

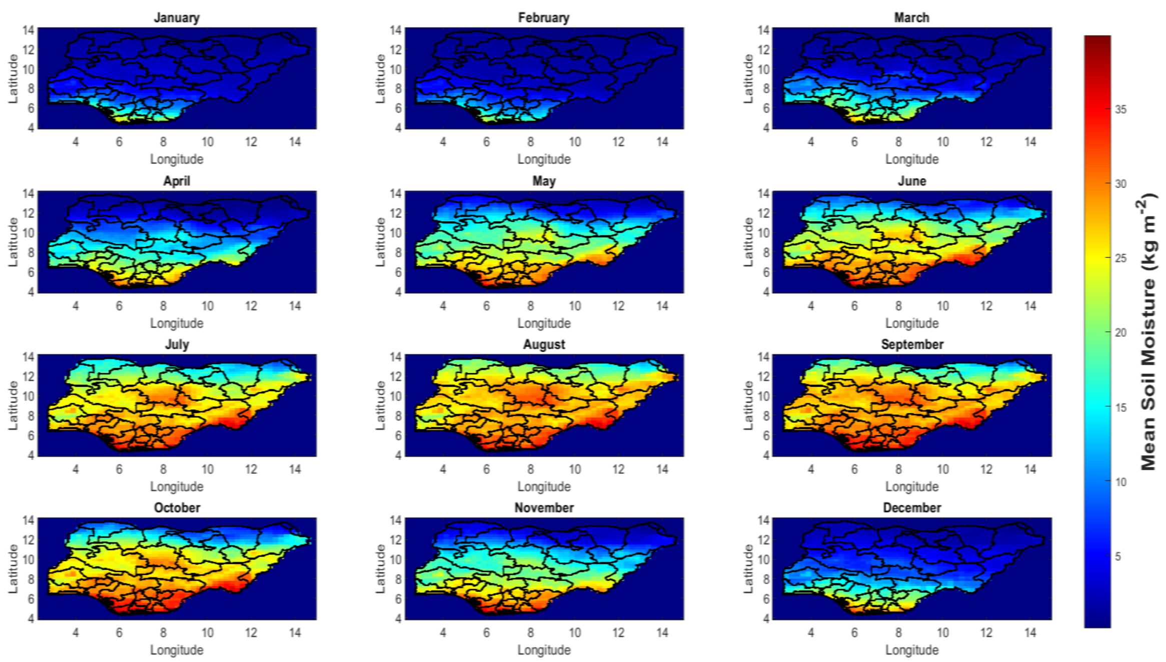

Figure 2: Monthly mean soil moisture climatology for Depth 1 (1983–2023).

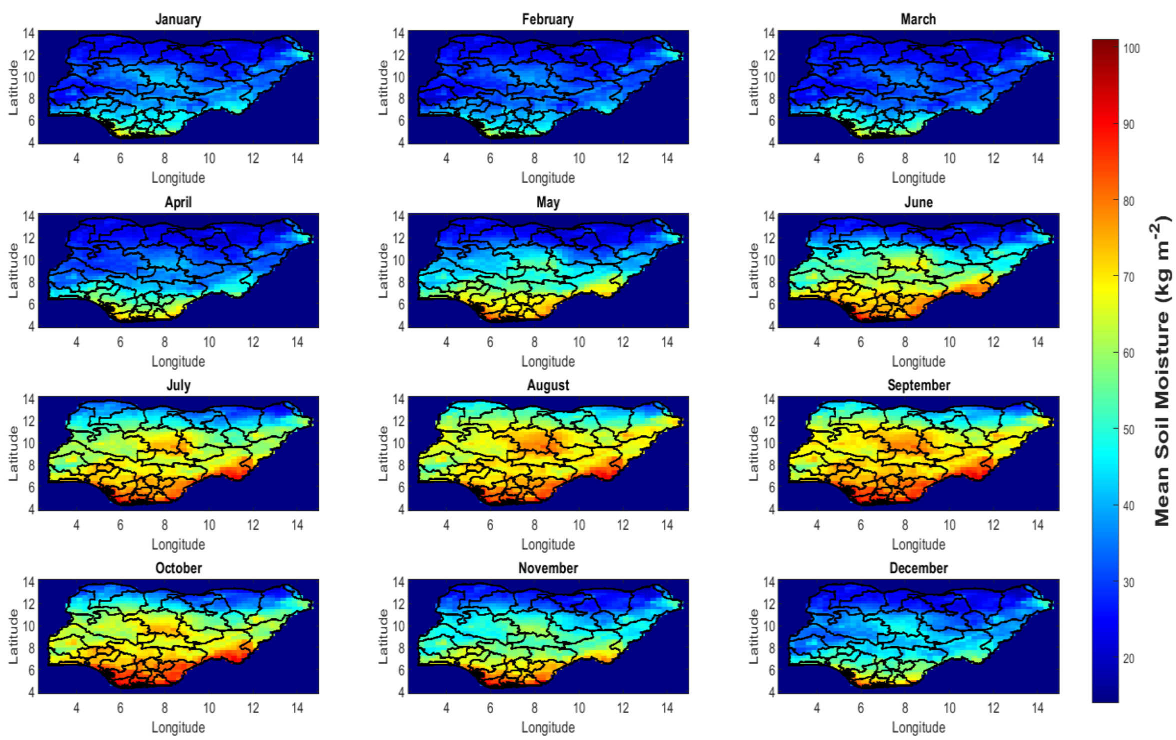

Figure 3: Monthly mean soil moisture climatology for Depth 2 (1983–2023).

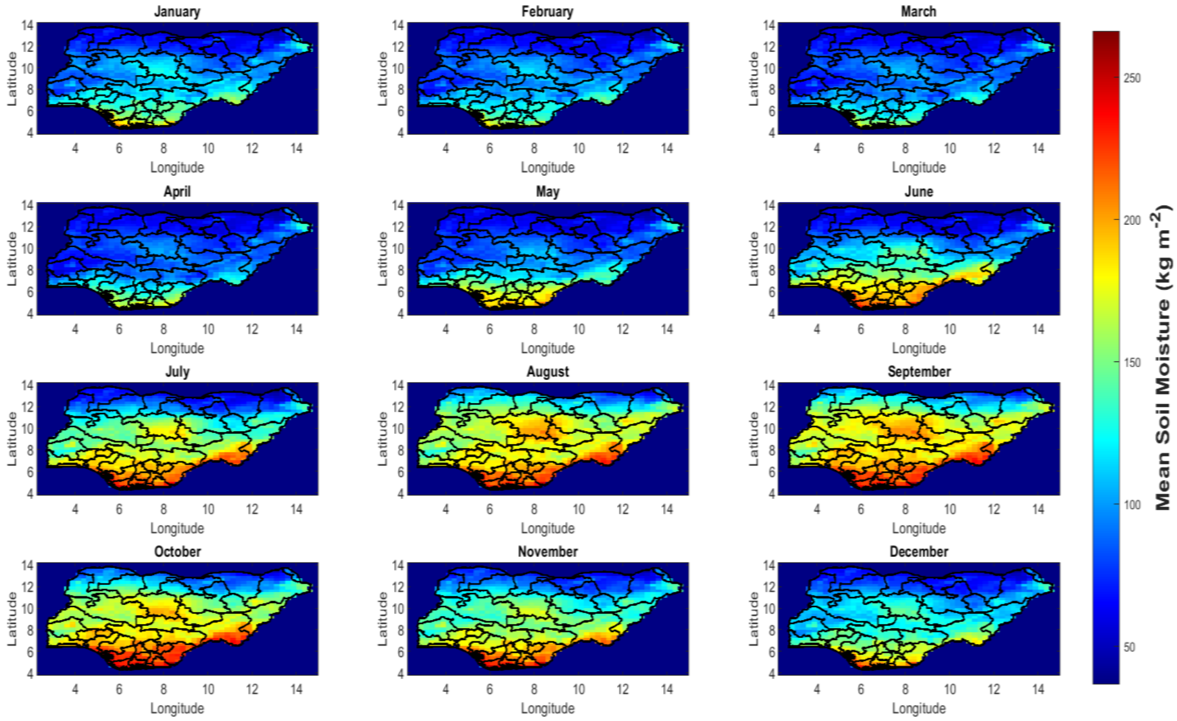

Figure 4: Monthly mean soil moisture climatology for Depth 3 (1983–2023).

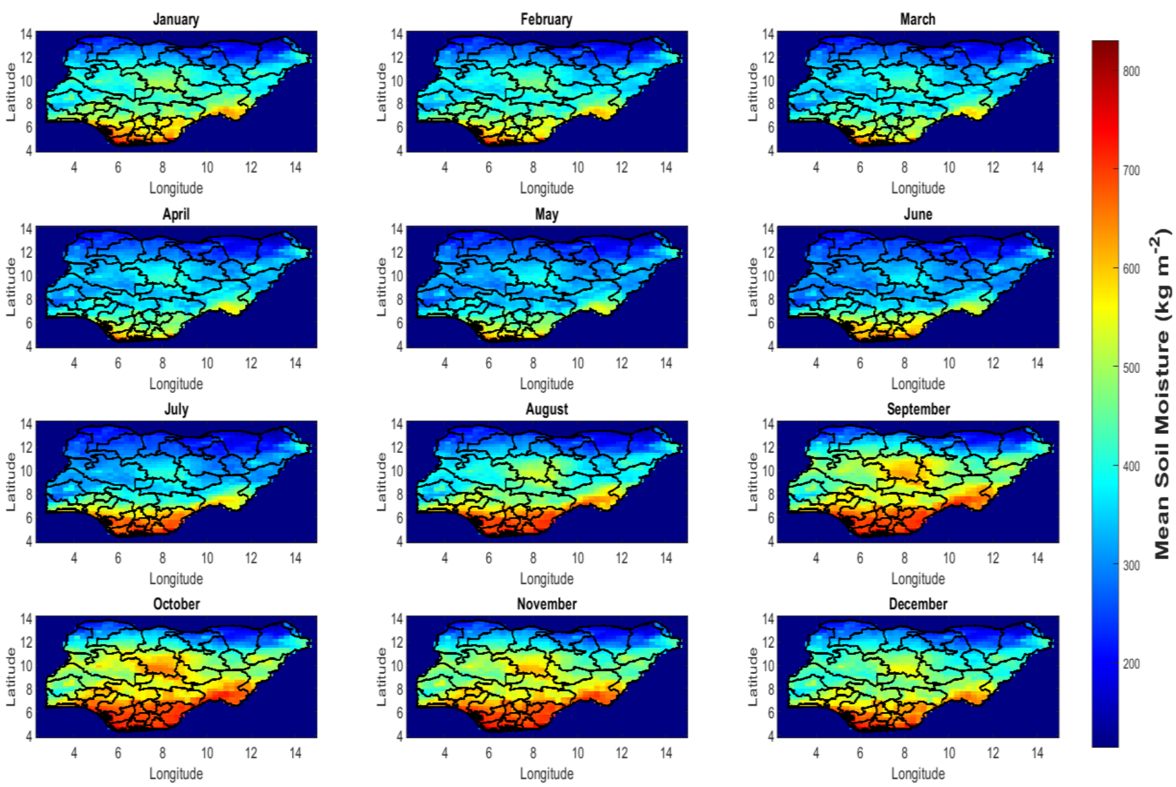

Figure 5: Monthly mean soil moisture climatology for Depth 4 (1983–2023).

Soil moisture magnitude and variability increase systematically with depth. The shallowest layer (Depth 1; ~0–10 cm) has the lowest moisture (typically 0–35 kg/m²) and responds most rapidly to weather. Underlying layers hold progressively more water: Depth 2 (~10–35 cm) ranges up to ~85 kg/m² in the south (dropping to ~50 kg/m² in the north), Depth 3 (~35–100 cm) reaches ~220 kg/m² in the south (~60 kg/m² in the north), and Depth 4 (below 100 cm) reaches ~700–750 kg/m² in southern zones (versus ~150–200 kg/m² in the far north). For instance, at a representative site in the deep south (4.625°N), mean moisture rises from ~33 kg/m² at Depth 1 to ~721 kg/m² at Depth 4. In contrast, a Sahelian site (13.625°N) increases from ~7 kg/m² at the surface to only ~243 kg/m² at Depth 4.

The soil moisture closely follows Nigeria's agroecological zoning, reflecting underlying climatic and soil differences. As shown in Figure 6, the spatial pattern of the long-term annual mean climatology depicts the north–south hydroclimatic gradient, with the driest conditions concentrated in the northern Sahel (~12–14°N) and progressively wetter soils toward the southern coast. In the northern Sahel (~12–14°N), mean moisture is minimal at all depths (for example, Depth 1 ~<7 kg/m², Depth 4 ~150–200 kg/m²) due to sandy soils and annual rainfall below ~500 mm. The Sudan Savanna (~10–12°N) is wetter (Depth 1 ~10–15 kg/m²) with slightly higher rainfall, but still exhibits high variability.

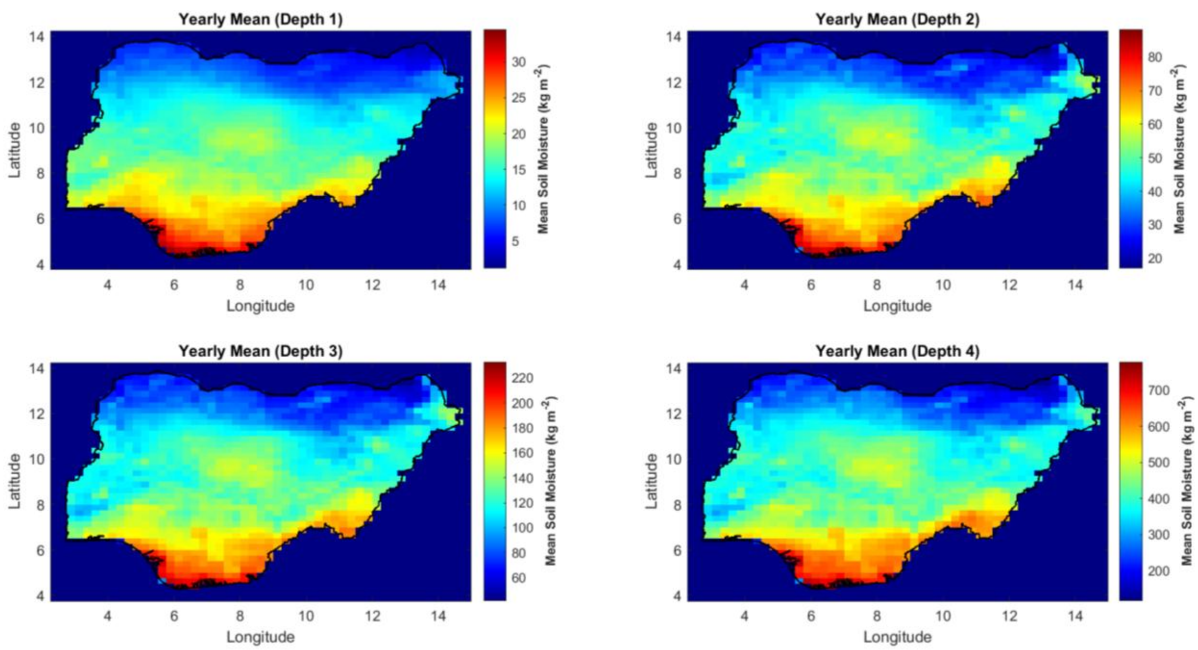

Figure 6: Long-term annual mean soil moisture climatology for Nigeria (1983–2023).

The Northern and Southern Guinea Savanna (~8–10°N) show higher mean moisture (Depth 1 ~15–20 kg/m²; Depth 4 ~300–400 kg/m²) under bimodal rains and denser vegetation. Further south, the Derived Savanna (~6–8°N) and Forest zone (~5–6°N) maintain even greater moisture (Depth 1 ~20–30 kg/m²), aided by clay-rich soils and year-round cover. The Coastal zone (near 4–5°N) exhibits the highest values overall, with surface moisture up to ~30–35 kg/m² in the annual mean. Notably, the variability (coefficient of variation) also decreases down the gradient: the Sahel sees CVs >70%, whereas southern forests have CVs <40%. Minor exceptions occur locally (for example, urbanized or deforested patches in the south can have lower moisture).

Strong seasonal cycles in soil moisture are evident, primarily driven by monsoonal precipitation. During the dry season (November–March), national soil moisture levels drop to about 20–40% of their wet-season peaks, especially in the shallow layer. Conversely, the onset of rains in April–May leads to a rapid increase, culminating in peak moisture in July–August. For example, surface moisture in southern Nigeria rises to

~30–35 kg/m² during July–September. After the monsoon peak, moisture gradually declines from October into December. The amplitude of this cycle is much larger in the north than in the south: typical seasonal coefficients of variation exceed ~80–100% in the Sahel but are only ~30–50% in the humid forest zone. In other words, northern soil moisture swings from near-zero in the dry months to moderate levels in the wet months, whereas southern soils retain relatively high moisture even in the local dry period.

3.2 Long-Term Soil Moisture Trends

Long-term soil moisture trends across Nigeria for the period 1983–2023 are illustrated in Figures 7 and 8, which show results from linear regression and Sen's slope analyses, respectively, and together highlight a pronounced latitudinal contrast. In the arid northern half of Nigeria, trends are predominantly positive, indicating soil moisture increases over time. For example, linear-regression slopes in the north reach up to about +0.06, +0.10, +0.40, and +2.0 kg/m²/yr at depths 1–4, respectively. By contrast, the humid south shows near-zero or slightly negative trends. In southern latitudes, some grid cells exhibit modest declines (e.g. roughly -0.003 kg/m²/yr at depth 4). The Sen's-slope maps mirror this pattern: northern areas gain up to +0.10 kg/m²/yr at depth 4, while southern regions include values as low as -0.0085 kg/m²/yr (depth 4). Spatially, increasing trends concentrate over the Sahel and savanna belts, whereas decreases appear in coastal and forest zones (with isolated stronger negatives in parts of the Niger Delta). East–west differences are minor, though positive trends in the eastern highlands are slightly stronger.

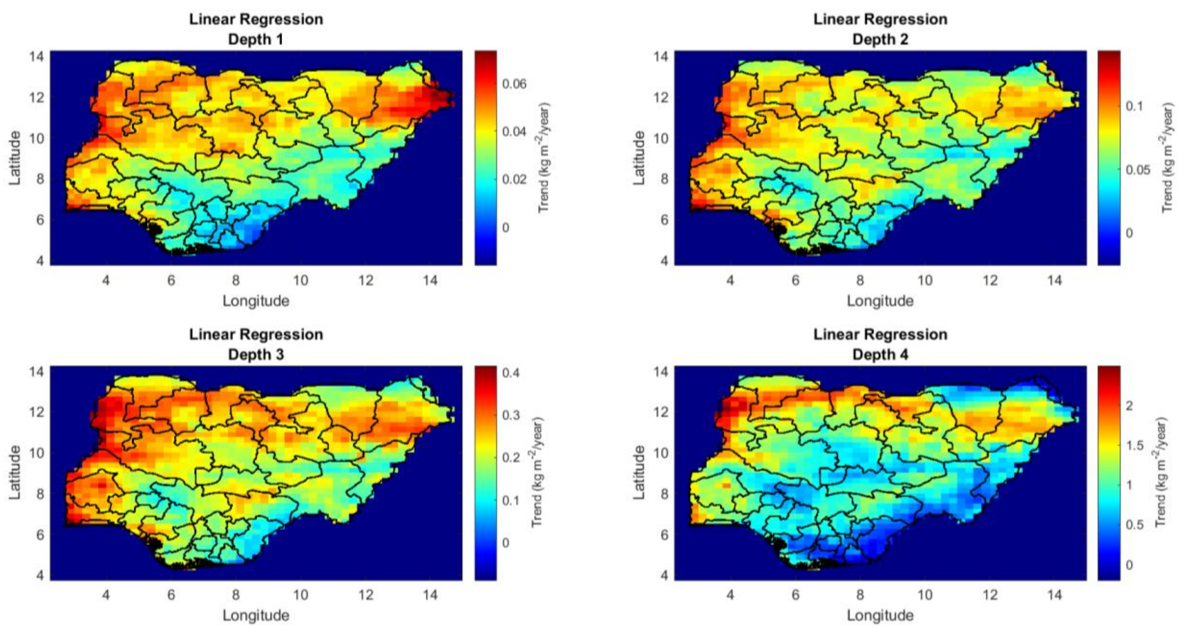

Figure 7: Linear regression trends of soil moisture across Nigeria (1983–2023).

Trend magnitudes amplify with depth. Surface trends (Depth 1) are very small: typical values in the north are only ~0.001–0.003 kg/m²/yr (Sen's method gives ~0.0014–0.0016 in some cases) and even smaller in the south (~0.0003–0.0007). Deeper layers show much larger changes: at Depth 2 the north sees ~0.0004–0.0007, and at Depth 3 ~0.005–0.006 kg/m²/yr. The strongest trends occur at Depth 4, with northern slopes up to ~0.10–0.11 kg/m²/yr (depending on method) and southern slopes reaching ~-0.016 to -0.021 kg/m²/yr. Thus, the deepest soil layers gain the most moisture (or lose the most in the south), while the surface shows only marginal change. This pattern implies that subsurface layers integrate long-term wetting signals (e.g. increased infiltration in the north), whereas the surface layer remains relatively buffered against secular shifts.

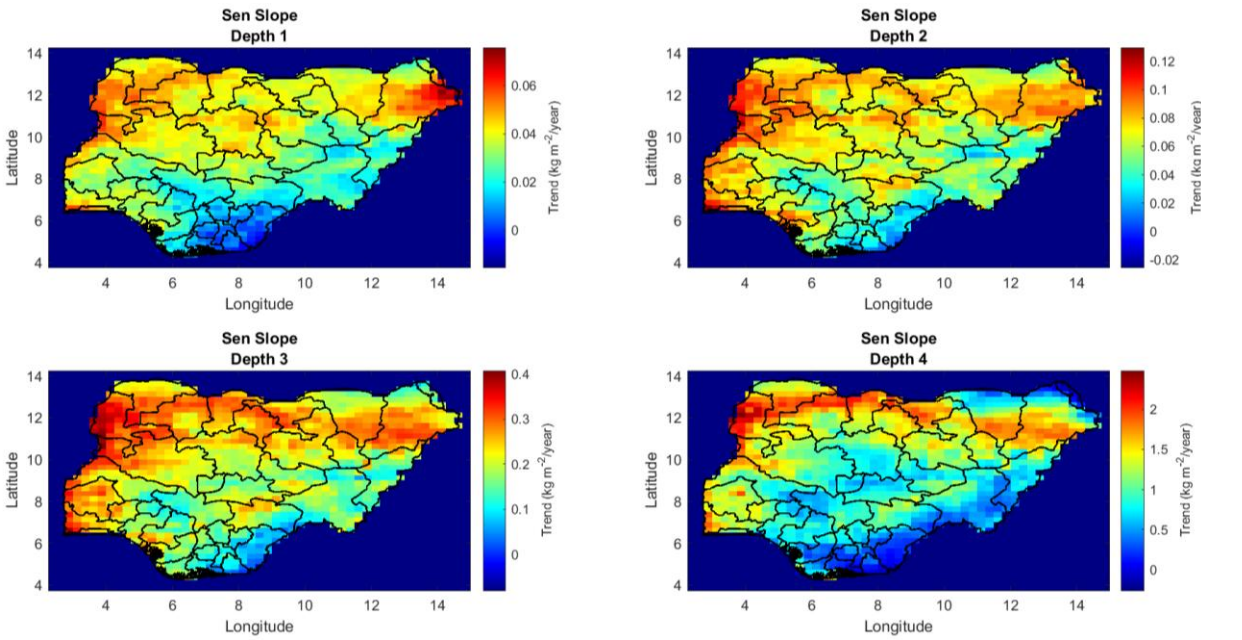

Figure 8: Sen's slope trends of soil moisture across Nigeria (1983–2023).

When aggregated by agroecological zone, trends show systematic contrasts. In the Sahel and Sudan Savanna (latitudes ~10–14°N), trends are consistently positive at all depths. For instance, Sen's-slope in these northern zones ranges from ~+0.0002–0.0008 kg/m²/yr at the surface to ~+0.08–0.10 kg/m²/yr at 100 cm. Both methods indicate pronounced wetting in these zones. Moving south, the Guinea Savanna (~7–10°N) shows moderate positive trends (~+0.001–0.006 kg/m²/yr across depths), reflecting its intermediate climate. In the southernmost zones (Derived Savanna, Forest, Coastal; ~4–8°N), trends are near-zero or slightly negative. In particular, deep soil in the Forest and Coastal zones shows declines (Sen's-slope on the order of -0.008 to -0.021 kg/m²/yr at 100 cm). Generally, the Northern zones are generally gaining soil moisture over time, whereas Southern zones are stable or losing moisture at depth.

Linear regression and Sen's slope yield consistent spatial patterns (northern wetting, southern drying), though Sen's slopes tend to be slightly lower in magnitude. For example, northern Depth 4 trends are ~+0.08–0.10 kg/m²/yr by Sen versus ~+0.09–0.11 by linear regression. Similarly, southern declines at depth are about -0.021 (Sen) versus -0.016 (LR). The agreement between methods confirms the robustness of the north–south contrast: where one finds wetting, so does the other. Sen's method, being less sensitive to outliers, depicts somewhat stronger declines in the south, whereas linear regression produces smoother gradient transitions. In practice, both estimators support the conclusion that northern Nigeria's soils have become wetter on average over the study period, while southern soils show only minor or negative changes.

3.3 Temporal Decomposition of Soil Moisture

The STL decomposition results for soil moisture at successive depths (Depths 1–4) are presented in Figures 9–12. These figures separate the time series into trend, seasonal, and residual components, revealing dominant long-term wetting in deeper soil layers and sharper seasonal oscillations in the near-surface layer. The long-term trend component shows net increases at all depths over 1983–2023. Specifically, mean moisture rose from ~14.6 to ~15.9 kg/m² at Depth 1 (+1.3 total), from ~46.3 to ~49.3 kg/m² at Depth 2 (+3.0), from ~118.5 to ~128.4 kg/m² at Depth 3 (+9.9), and from ~373 to ~420.6 kg/m² at Depth 4 (+47.6). These correspond to average slopes of roughly +0.03, +0.07, +0.24, and +1.1 kg/m² per year at depths 1–4. The trend rises most strongly in the 1980s–90s and has slowed or slightly reversed after ~2015, particularly at the surface.

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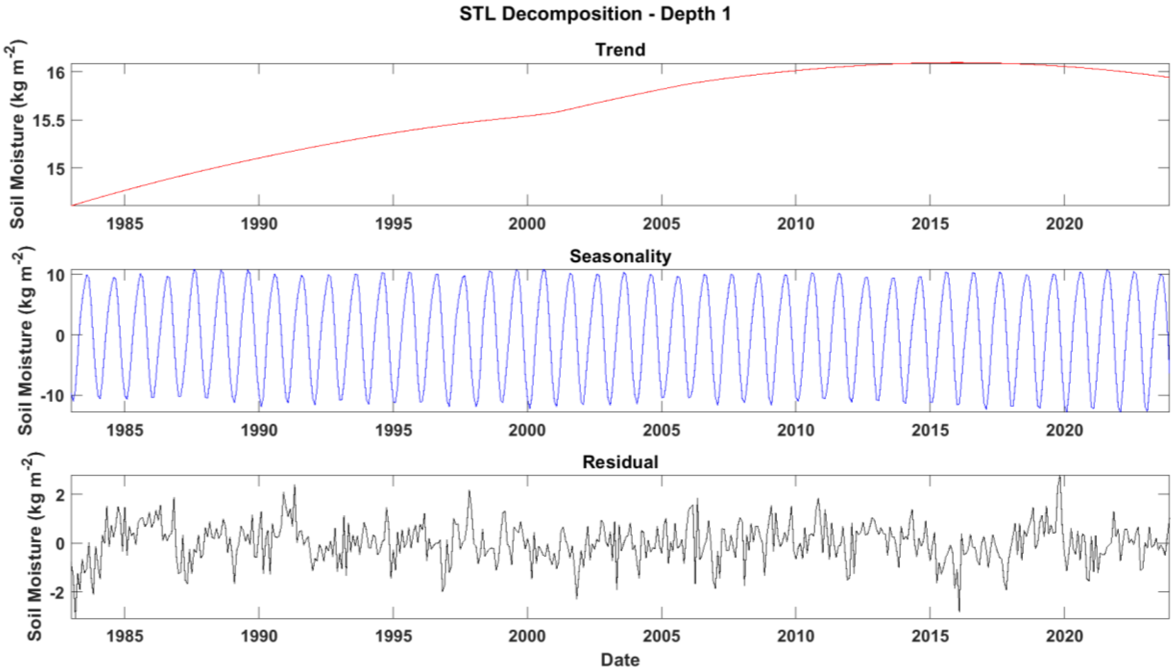

Figure 9: STL decomposition of soil moisture time series for Depth 1 (1983–2023).

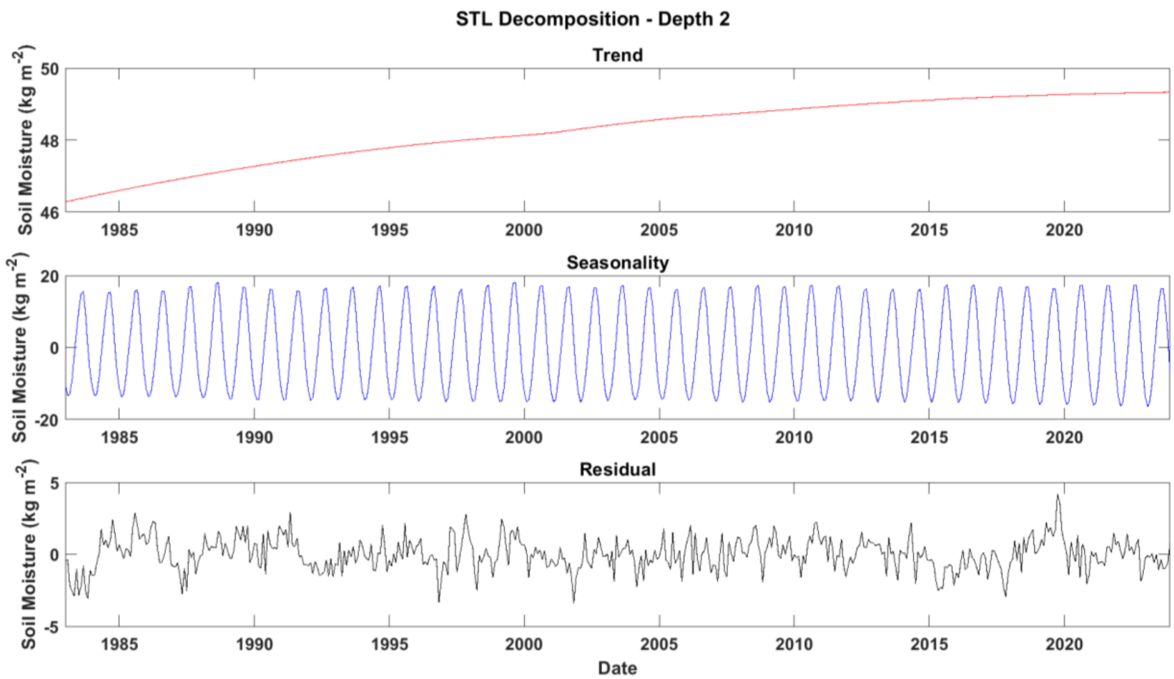

Figure 10: STL decomposition of soil moisture time series for Depth 2 (1983–2023).

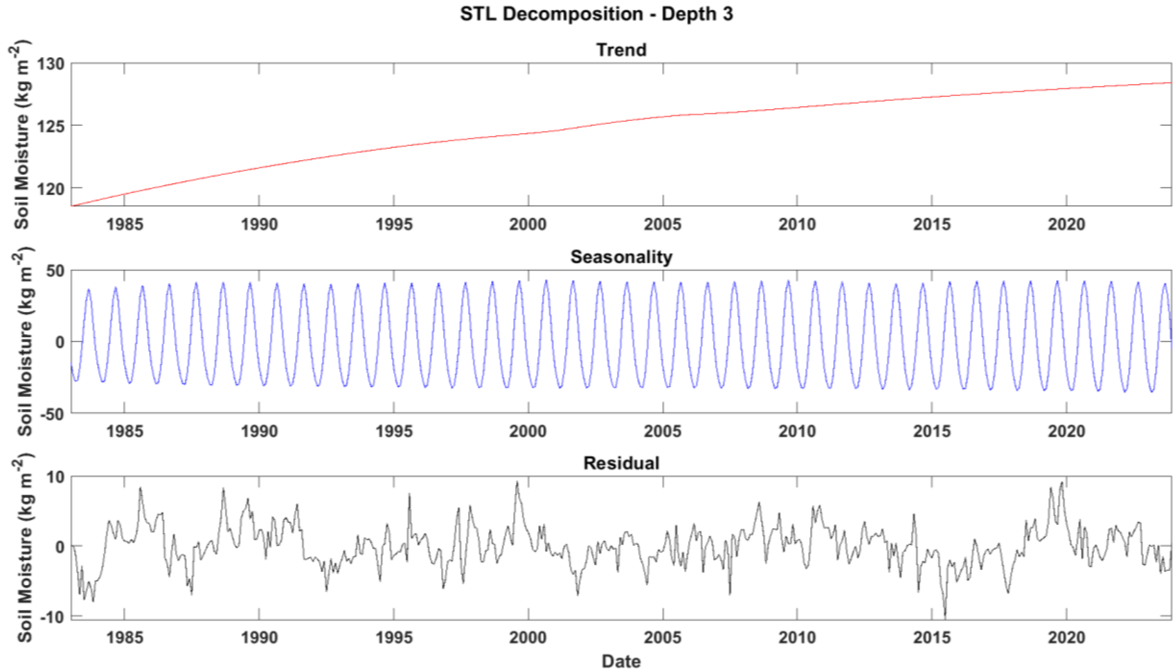

Figure 11: STL decomposition of soil moisture time series for Depth 3 (1983–2023)

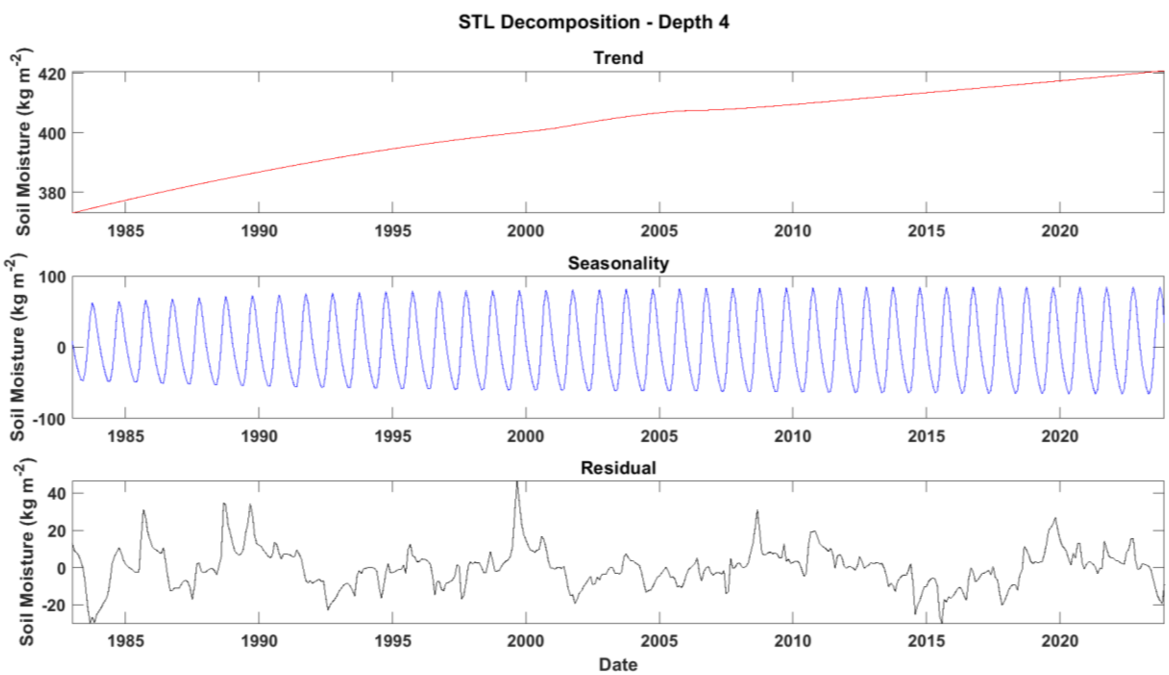

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Figure 12: STL decomposition of soil moisture time series for Depth 4 (1983–2023).

The seasonal component is remarkably regular and grows with depth. Annual oscillations (relative to the long-term mean) span approximately ±10 kg/m² at Depth 1, ±20 kg/m² at Depth 2, ±50 kg/m² at Depth 3, and ±100 kg/m² at Depth 4. Wet-season peaks occur in mid-summer (July–August) and dry-season troughs in late winter (February–March) across all depths. The surface layers exhibit sharper, more abrupt seasonal swings in response to rainfall onset, whereas deeper layers show smoother, more damped cycles due to soil buffering and slower recharge. The residual (irregular) component is relatively small compared to trend and seasonality. At Depth 1 residuals mostly lie within ±2 kg/m²; they grow to roughly ±5 kg/m² at Depth 2, ±10 at Depth 3, and between -20 and +40 kg/m² at Depth 4. Occasional large deviations (e.g. a spike of +40 kg/m² around 2000 at Depth 4) correspond to extreme wet or dry events. In general, deeper layers show larger residual fluctuations, consistent with amplification of anomalies via subsurface flow. The decomposition reveals a persistent wetting trend at deeper layers, combined with a stable annual cycle. Deeper soils accumulate much of the increase: Depth 4 gained nearly 48 kg/m² over 42 years, while the surface gained only ~1.3 kg/m². The seasonal amplitude likewise intensifies with depth (tenfold from surface to deep). The results indicate that deeper soil moisture reflects long-term climate trends, while surface layers respond to short-term annual variability.

4. DISCUSSION

The observed soil moisture patterns across Nigeria are characterized by a pronounced north–south contrast that is consistent with established West African hydroclimatic zones. While the southern coastal and forest regions maintain higher absolute soil moisture levels and the northern Sahel remains comparatively dry, the relevance of these patterns lies in how they evolve seasonally and over longer timescales. Seasonal variability reflects the dominant influence of the West African monsoon, with larger seasonal amplitudes in northern Nigeria and more muted fluctuations in the humid south. These spatial and seasonal characteristics are consistent with the role of soil moisture in regulating infiltration, runoff, and evapotranspiration, with implications for ecosystem functioning and drought resilience (Liao *et al*., 2017).

Long-term trends reveal a marked latitudinal asymmetry, with pronounced wetting in northern Nigeria and near-zero or slightly negative trends in the south. This divergence contrasts with some continental-scale assessments that reported widespread drying across West African savannas during shorter analysis periods (Yuan *et al*., 2022). The difference is likely attributable to temporal coverage. By spanning 1983–2023, this study captures post-drought recovery processes in northern Nigeria that followed the severe droughts of the 1970s–1980s. Observational studies indicate that rainfall in northern Nigeria increased after the late 1980s, with longer rainy seasons and enhanced late-season precipitation (Usman *et al*., 2018), conditions that favor gradual soil moisture recharge and accumulation at depth. The northern wetting trends observed here are therefore consistent with documented hydroclimatic recovery rather than short-term variability.

In contrast, the absence of sustained wetting, and the emergence of weak drying signals, in southern Nigeria requires more careful interpretation. Although the southern zones receive abundant rainfall, higher precipitation does not necessarily translate into increasing soil moisture storage. Rising air temperatures can enhance evapotranspiration, thereby offsetting rainfall inputs and limiting net soil water gains (Sheffield & Wood, 2008; Wang *et al*., 2019). In addition, land-use and land-cover changes, including deforestation, agricultural expansion, and urbanization, can reduce infiltration capacity, alter soil structure, and increase surface runoff, ultimately constraining soil moisture recharge (Liao *et al*., 2017; Yuan *et al*., 2022). Anthropogenic influences such as irrigation withdrawals and groundwater abstraction may further modify subsurface moisture dynamics, even in humid environments (Qiu *et al*., 2015; Wang *et al*., 2019). While these mechanisms are supported by the literature, their relative contributions cannot be directly quantified here and should therefore be regarded as plausible drivers rather than definitive causes of the southern drying tendency.

A notable result is the systematic amplification of trends with soil depth. Deeper layers exhibit larger and more persistent changes than the surface, indicating that subsurface soils integrate hydrological signals over longer timescales. Surface moisture responds rapidly to short-term weather variability, whereas deeper layers reflect cumulative infiltration and storage processes. This vertical stratification is consistent with earlier findings that deeper soils provide a more stable moisture reservoir and are better indicators of long-term hydroclimatic change (Hao *et al*., 2016). The temporal decomposition further supports this interpretation, showing a persistent deep-soil trend accompanied by a relatively stable annual cycle. Similar depth-consistent drying and wetting patterns have been reported at continental scales, with strong correspondence between surface and subsurface trends (Lal *et al*., 2023).

These interpretations are constrained by data availability and methodological considerations. In-situ soil moisture observations in Nigeria are sparse, necessitating reliance on merged satellite-derived products for spatially continuous analysis. Such products have been widely used to identify regional soil moisture trends (Hagan *et al*., 2020; Yuan *et al*., 2022; Cai *et al*., 2023), but they are subject to uncertainties related to sensor penetration depth, vegetation effects, and terrain complexity (Houben *et al*., 2025). Although robust statistical approaches were applied to reduce bias, modeled soil moisture remains sensitive to forcing data quality and land-surface heterogeneity, including irrigation and soil texture variability (Qiu *et al*., 2015; Kumar *et al*., 2024). These limitations highlight the need for improved long-term, high-resolution soil moisture observations across West Africa.

The documented soil moisture patterns have important implications for agriculture and climate adaptation. Soil moisture is a key control on crop productivity in rain-fed systems, where both deficits and excesses can reduce yields (William, 2024). The observed wetting trend in northern Nigeria may enhance agricultural potential in a region historically prone to drought (Yuan *et al*., 2022), although high interannual variability and episodic dry spells remain critical challenges. In the south, stable or declining soil moisture at depth, combined with rising evapotranspiration demand, may increase vulnerability to agricultural stress despite high rainfall. More broadly, soil moisture deficits have been linked to socioeconomic and environmental pressures across Africa (Yuan *et al*., 2022). Integrating soil moisture information into land and water management frameworks is therefore essential for effective climate adaptation. The spatially and vertically resolved insights provided here support the development of region-specific agricultural strategies and water-resource planning, in line with broader climate and desertification policy objectives (Yuan *et al*., 2022; Ogunrinde *et al*., 2024).

5. CONCLUSION

This study provides a comprehensive assessment of the spatial and temporal variability of soil moisture across Nigeria using 41 years (1983–2023) of TAMSAT gridded data. The findings reveal that soil moisture distribution strongly reflects Nigeria's climatic and agroecological zonation, with a clear north–south gradient that mirrors rainfall and vegetation patterns. The southern coastal and forest regions consistently exhibit high and stable soil moisture due to frequent precipitation, dense vegetation, and clay-rich soils, while the northern Sahel and Sudan Savannas remain markedly dry with high interannual variability, reflecting their semi-arid climatic conditions and sandy soil composition. Trend analyses based on both linear regression and Sen's slope estimators indicate a general wetting tendency over much of northern and central Nigeria, particularly at deeper soil layers. This pattern indicates a gradual increase in subsurface water storage and infiltration capacity over the study period, reflecting the combined influence of long-term climatic changes and land–climate interactions. In contrast, localized drying observed in parts of the humid southern zones may stem from anthropogenic pressures, including deforestation, land-use transformation, and rapid urbanization. The STL decomposition further reveals that these long-term shifts occur within a persistent annual cycle, emphasizing that soil moisture variability in Nigeria remains predominantly seasonal while exhibiting a gradually changing long-term mean. Future research should prioritize expanded validation using long-term in-situ soil moisture observations, particularly through integration with available ISMN stations and emerging national monitoring efforts. In addition, coupling soil moisture trend analyses with high-resolution land-use and land-cover change datasets would enable a more explicit attribution of observed drying and wetting patterns to climatic versus anthropogenic drivers.

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